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Technical paper

Parametric CAD/CAE integration using a common data model

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ABSTRACT

This paper proposes a CAD/CAE integration method using a "common data model" (CDM) containing all the required parametric information for both CAD modeling and CAE analysis. CDM is automatically generated by a knowledge embedded program code. The CDM is used as a parametric data model repository and the supply source of input for those associative entities of CAD and CAE models and thus maintaining the associative dependences among them. The structure as well as the data flow in the CDM is governed according to the general and widely used design processes. Thus designers can relate the expected scenarios with the engineering changes proposed and can take the parametric actions accordingly. CDM acts as the centralized parametric input for computer modeling software tools through their APIs. Throughout the design process the common data model gets modified during each development cycle according to designer's intent, the changes in it are consistently reflected in both CAD and CAE models through regenerations and analysis iterations semi-automatically. The same data model in a suitable file format can be used to work with different CAD and CAE packages. As CDM, CAD and CAE work as different modules interconnected through a develop software prototype package which integrates APIs and knowledge rules embedded in the engineering procedures. However, each of the software tools used for each purpose can vary as per the original data requirement without hindering the process structure. The data model is reusable and the whole process is automated as far as possible so that the embedded expertise in the cycles of the adaptive design and manufacturing can be consistently applied iteratively during product development processes. Also being a data file in a suitable format generated via computer programming, the CDM is convenient to record and store information associated to all the product design revisions.

1. Introduction

Modern CAD modeling and CAE analysis cycles have become an inherent part of today's product development process. There is a variety of commercial CAD software tools such as Solid Works^{TM}, Pro/Engineer^{TM} etc., and CAE analysis software tools like Ansys^{TM} and NX Nastran^{TM} which are widely used in the industry. But for most of these tools the focus is usually on either CAD or CAE application separately and lacks complete potential to handle the other. In most of the time, a design engineer has to work with two or more independent software packages for modeling and analysis and yet has to maintain the associativity by checking the constraints applied throughout the engineering processes. However, due to the tedious dependency relations and the lack of management tools, it is difficult to avoid losing model integrity. Thus it is desirable to integrate CAD and CAE in order to complete every design cycle effectively. In modern CAE software tools, the geometry generated in CAD can be directly taken as input for analysis but the complex geometry has to be modified and simplified in order to get an effective and quick result. Further, the data flow process, i.e. from CAD to CAE, is a one-way transition and the loss of information from CAD has created repetitive CAE modeling tasks which become the major hurdles to reflect changes through each CAD/CAE cycle.

Some of the major issues involved in CAD and CAE integration are summarized as follows: (1) information losses; (2) compatibility issues between data structures; (3) breakdown of associations; (4) lack of reusability of knowledge; (5) the conflict of complex geometry and its analysis simplification requirement; (6) loss of design expertise; (7) difficulties in automation of the design process; (8) unacceptable time associated with the total design cycles; (9) geometry simplification of CAD model and the conversion to FEA model for mesh generation and analysis.

Many efforts have been made to work with standard file formats such as STEP to convey the design intent along with CAD. Some of the issues with this technique are that the generation of STEP files that takes considerable amount of translation and repair effort. On the one hand, some semantically associated data in the CAD model gets lost; on the other hand, if the designer does not want to pass on all the design data along with the model as the intellectual property is concerned, he or she would be difficult to manage with a

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Nomenclature

μ	Viscosity, cp
ρl, ρg	Density of liquid, gas, lb/ft^3
API$^\circ$	Specific Gravity of oil
CD	Drag coefficient of particle
dm	Droplet diameter, micron
D	Diameter of vessel, in. or ft
E	Joint efficiency
h	Liquid level in vessel, in.
ht	Skirt height, in.
H	Vessel total height, in.
idx	Inlet diverter parameters, in.
L	Shell length, in.
Leff	Effective length, in.
Lss	Seam to seam length, in.
MW	Molecular weight
MEx	Mist extractor parameters, in.
P	Operating pressure, psi
Ql	Liquid flow, bpd
Qg	Gas capacity, MMscfd
RE	Reynold's number
S	Max. Stress, psi
SGg	Specific gravity of gas
t	Thickness parameters, in.
T	Temperature, °F.
vbx	Vortex breaker parameters, in.
vt	Terminal velocity, ft/s
W	Operating weight, lb
Z	Compressibility factor
API	Application Programming Interface
CAD	Computer Aided Drawing
CAE	Computer Aided Engineering
CDM	Common Data Model
FEA	Finite Element Analysis
GUI	Graphical User Interface
KBE	Knowledge Based Engineering.

standard data format. It is advantageous to use parametric modeling for purpose of isolation and control of design data from various computer models.

Therefore, a method of integrating CAD and CAE at parametric level is proposed with the help of a common data structure sharing information with all the computer software models, and it is hereafter called a Common Data Model (CDM). Rather than integrating various models themselves in a pair-wise specific interfaces between individual packages, all the parametric information associated with the computer models is integrated in a neutral data model outside those specific commercial software environments.

This paper reports a research effort that automatically creates the common data model (CDM) by programming embedded engineering concepts, expert knowledge and design standards into a prototype software package and automates most of the product development processes with minimum user interfaces via commercial CAD and CAE APIs. Thus combining and automating parametric CAD and CAE generations can increase the efficiencies of the both processes and considerably reduce the design cycle time. To deal with the geometry complexities and the overall time required for detailed CAE analysis cycles, a dual-loop design process is adopted. In this approach, during initial design stage, the skeletal mid-plane conceptual model for the design object is created, for which, in CAE analysis, the mesh model comprises of only 2D elements thus the calculation takes much less time as compared to a detailed 3D mesh model. After the basic structure of the design object is finalized using the mid-plane model, the design then enters the next loop, a detailed design process, in which the design object is modeled as 3D solid with all the design details; hence, the CAE model associated is similarly made of 3D FE elements. Because the major design structure has been finalized during the initial mid-plane stage, the detailed model requires less number of iterations to check those localized areas. Note that as in the initial stage, the mid-plane CAE analysis replaces usual detailed analysis with many cycles of iterations, the effectiveness of the overall approach increases and also the total product development time required decreases dramatically.

2. Literature review

Since a CAD system has the various tools to model product geometry while CAE need product geometry as the input for FEA analysis, under the pressure of cycle time for product development, there have been numerous efforts for integration and automation of the computer design and analysis process. Ideally, CAD/CAE integration can be achieved via geometry information sharing and derivation throughout the product evolvement with constant changes. However, historically, the integration of CAD and CAE has been a great challenge in the field of engineering informatics. Some early efforts in model and analysis integration involved automated conversion of CAD to FEM. Yip et al. [1] focussed on a *knowledge-intensive CAD (KIC)* which includes integration of design lifecycle and engineering knowledge with CAD, including CAE results; but they did not show how these two aspects interact automatically. Anumba [2] did some of the early work to explore the advantages of integrated CAD systems within a structural engineering context. He discussed and explored basic difficulties associated with integrated CAD along with proposed data structure for bidirectional coordination of graphical and non-graphical information. But the scope was limited to CAD only and was one of the preliminary studies. Shephard et al. [3] developed a method to support *Simulation Based Design*via CAD model simplification and data management. It seems the modular design environment works well in a controlled interactive design and analysis setting, but is not clear how the associative design and analysis parameter relations introduced by engineering constraints are maintained consistently. Schreier [4] discuss development of CAD and CAE software tools towards each other and the trends of the software vendors to close the gap between them. He also discusses the benefits of CAD–CAE integration along with the benefits of compatibility between various CAD and CAE software tools. The article also describes various new developments in software tools such as "CAD embedded analysis". The major objective of author is to describe the ease of associativity between modern CAE and CAE software tools.

In order to integrate information between CAD and CAE, a middleware development approach is also favored widely. Propagation of changes is also managed by optimization methods and embedded knowledge. Dr. Van der Velden [5] developed a GUI based system called iSIGHT-FD which manages the computer software required to execute simulation design process. It propagates the changes in CAD automatically and changes analysis along with Meshing of entire CAD model without any geometry simplification. Author proposed parametric CAE output using platform to utilize multiple CAD and CAE software tools. Foucault et al. [6] addressed the mesh quality enhancement in conversion of CAD model to finite element model for analysis. Xu and Chen [7] developed a fully automated product design system with CAD–CAE integration and multi-object optimization. Authors employed integration of FEM and iSIGHT optimization for decision making in product development of simple objects. The major disadvantage of method is to develop a complex optimization algorithm along with soft code for FEM and CAD all of which has to be product specific thus the study to the study is good for preliminary simple design but the system is very hard to be modified for more detailed and complex engineering problems.

2.1. *The current state of art for CAD and CAE integration*

Some of the earlier efforts manage considerable automation advance as well as good association of model information. Wei [8] proposed automatic generation of finite element analysis using the ontology based approach by defining the fundamental analysis modeling knowledge into a set of formal ontology. Aziz and Chassapis [9] developed a knowledge based system for integrated engineering design process from the initial concept to production using the feature based modeling and design for CAD and FE analysis. The system utilizes manufacturing and design knowledge bases. Chapman and Pinfold [10] discussed limitations of traditional CAD and advantages of using KBE along with FE analysis with the help of a "concept development tool" for efficient organization information flow and as architecture for the effective implementation of rapid and iterative design solutions. It was one of the initial studies to enhance the capabilities of existing CAD and for knowledge utilization and sharing. Colombo et al. [11] addressed the need of software to support engineers in complex design and proposed KBS tools. Author also suggests a conceptual framework and philosophical approach for classification of knowledge types along with relationships between various functions using mathematical model to define ontology. Xu and Wang [12] proposed using of *Multi Model Technology (MMT)* for integration of CAD/CAE/CAM. MMT uses object-oriented technology (OT) into the product modeling process together with feature based modeling technology. It includes use of a single basic solid CAD model to generate all the other required models in the subsequent layers of product development process. Features are defined to maintain the associativity between them and feature manipulation is used to maintain integration between CAD and FEA models. In application studies, Yan and Jiang [13] proposed an integrated method of CAD/CAE/CAM for the development of duel mass flywheel. The interference between various software tools is obtained by using a uniform product data model. Method used specialized software tools to evaluate analysis such as welding strength. One of the major issues involved is that the system uses a large number of software tools and thus making interoperability and exchange between models complicated.

Most of the work done before was to develop initial product model and lacked recursive nature of an actual design process. Albers et al. [14] proposed a strategy for the development of engine crankshaft with the integration for CAD, CAE and genetic algorithm. A Java based interface is used to integrate CAD and CAE. Genetic algorithms are used as optimization tool along with graph analysis. But author does not propose any means to complete the design loop. Cao et al. [15] developed a middleware to transform CAD models into acceptable CAE mesh model, i.e. HEDP (High End Digital Prototyping). It can manage model simplification and defeaturing of CAD models to make it acceptable to FEA meshing and also get quick results; but the integration is one-way traffic and lacks the recursive loop support, As during a design process, the object to be designed goes through multiple design loops before being finalized, thus the designer needs to recalculate the parameters involved several times. For effective integration of CAD and CAE, along with parametric modeling, engineering knowledge embedment into the process can reduce the overall time for the design and can incorporate design standards and codes into computer program which can be reusable. Penoyer et al. [16] used KBE along with CAD, CAE and CAM for complete product development. The approach was GUI based with KBE to manage majority of the product lifecycle process. But the author does make use of embedded knowledge rather it is suggested to use direct user interface thus giving lower automation in the process.

2.2. *Analysis of CAD and CAE integration problems and research required*

From above efforts we can realize some that there are some major hurdles in integration of CAD and CAE, but there has been independent work done to solve these problems to improve current CAD design and computer analysis. Some of the leading work done can be categorized according to specific problems as below.

2.2.1. *Data interoperability*

One of the major difficulties in integration of CAD and CAE is association of design data between them. Data associated with CAD is usually geometric however FE model requires mesh and material related data associated with the geometric model imported from CAD. Hamri and Lèon [17] suggested using *polyhedral* model as an intermediate model between CAD and FE model for interoperability. They recognized the need of re-analyzing the same CAD model multiple times with modifications in the evolution of product design phases. Arabshahi et al. [18] identified the potential and did some of the earliest work on CAD–FEA integration. Objective behind this study was easier, more robust and faster transformation from CAD to FEA. Author describes the requirements for an automated system for CAD to FEM transformation with major focus on attribute editing and two way link between FEA attributes and geometry along with feature recognition. Joel Johansson [19] proposed an integrated KBE, CAD and FEM for automated system for preliminary production preparations and for complete automation of the process. Some of the issues that the system encounters are compatibility with available commercial CAD and CAE software tools and difficulties in order to develop complicated models. Su and Wakelam [20] worked on creating an intelligent hybrid system to integrate various CAD, CAE and CAM tools in design process using a blend of rule based system, artificial neural networks (ANNs), genetic algorithm (GA) into a single environment using parametric approach for model generation and rule based approach to control the design environment. CAD & CAE data model are different, therefore the geometry has to be further processed, e.g. converting to mid-plane model, or simplifying the model, etc. It is convenient for integration if there is a common platform between CAD and CAE for information of both the models to co-exist.

2.2.2. *Long design cycle time*

One of the major issues in improvement of current design process is to reduce the overall time required. It is desirable to reduce time associated with the process since it reduces the required resources as well as development costs. Resh [21] proposed use of CAE to shorten the development cycle time. Author suggested use of CAE for initial evaluation as well as suggested that the process needs to be reformed in order to reduce duplication and human errors. Kagan et al. [22] managed product development using an integrated CAD and CAE software which uses B-spline model in order to reduce the development time, cost associated and simpler fine tuning process for the product. They developed a modeling method in which same B-spline model was used for both CAD and CAE thus eliminating the need for conversion, but the study does not utilize any automation or use of engineering knowledge and standards in process.

2.2.3. *Managing complete design modeling with integrated engineering innovation systems*

As mentioned earlier one of the difficult tasks in CAD and CAE integration is association of data and managing the models to avoid any loss of information. Numerous attempts to solve this problem used knowledge embedded or knowledge based systems to manage the semantic relationships. Computer modeling coupled with engineering knowledge can manage the entire design process effectively. Penoyar et al. [23] discuss the importance of KBE in product lifecycle management and integration of CAD and KBE using API with the help of same software tool for KBE as the CAD system developer. A mechanism for the API for CAD is also discussed to accommodate designer's intent, to manage engineering knowledge and possible changes. Author further suggests use of Database to manage all the design data and knowledge with the proposed system. Zeng et al. [24] proposed a multi-representational architecture (MRA) to facilitate the transformation of information from design models to various support analysis models. The major focus was on ABBs (Analysis Building Blocks) for solid mechanics and thermal systems that generate FEA in order to bridge the gap between design and analysis model. Xu et al. [25] proposed to integrate CAD/CAM/CAE based on CATIA for the end-to-end process in cylinder head development using Multi Model Technology (MMT) to create consistent and associated CAD models. Chen et al. [26] suggested use of Unified feature modeling for integration of CAD and CAx for the process of product development process. The feature was defined as a "relationship object associating geometric entities". The author utilized knowledge base and unified feature information database for information sharing, consistency and control among different models. The work is primarily based on feature association and unification concepts which include three-level geometric and non-geometric relations. Bossak [27] was one of the earliest to explore the area of computer modeling and analysis for complete product development with integration of various computer based technologies and tools along with product data management (PDM) technology. Smit and Bronsvoort [28] discuss various previous approaches for design and analysis model integration and also suggest a new method by integrating an analysis view into multiple view feature modeling using automation and analysis knowledge. Author provides clear discretion of design model and analysis model and their differences. They also discuss the idea of maintaining multiple views of the model a time and modification of views and design by feature conversion. As per their definition, *"An analysis view in the multiple view feature modeling approach should be a view of the product that is suitable for an engineer to perform analysis with."*

2.3. Feature based approach for CAD and CAE integration

Feature is essentially defines the basic structures that made up a particular model, thus a model is built up with one or more features as building blocks. In conventional modeling process, initially a base feature is created and the is further enhanced by adding other features or simply adding more details to it until required model is obtained. Development of features various follow the designer's intent and thus are subjected to changes as the design progress. Thus a model based on features can be changed by manipulating the features which in turns can be used to reduce the development time. If features are integrated with parameters and other features, changes made in one feature can be successfully propagated through the entire design [29]. Monedero [30] did some of the early work with parametric design and integrating design methods and provides basic definitions associated with parametric design and modeling. Author also lists problems associated with integrations such as lack of appropriate instruments to modify interactively the model once it has been created and going back and forth between design processes. Deng et al. [31] incorporated the use of feature based modeling and analysis for CAD and CAE integration where various features associated with both CAD and CAE including all geometric and non-geometric ones. The prototype software for injection molded product design tried a feature mapping method for CAE feature simplification such as ribs. Kao et al. [32] discussed the parametric and feature based automatic generation of CAD for thread rolling die-plate geometry to regenerate the model with varying set of parameters and features with the use of an external spreadsheet file to be used as a source of parameters for CAD/CAM/CAE. Though the changes were automatic, interface was GUI using a predefined template. All the related parameters had to be calculated beforehand and needs to be written into spreadsheet and corresponding changes are also required to be made interactively. Chen et al. [33] discussed semantics of design and machining feature and identifying information entities, relations, constraints in each view and further generalizing common entities in order to develop a consistent product information model. Use of features is proposed as information medium in order to integrate conceptual design, detailed design and process planning are discussed along with feature association and unification are described in with relation to unified feature modeling scheme for information sharing and consistency control. Chen et al. [34] made use of unified feature for integration of CAD and CAx models for concurrent engineering for information sharing and consistency control between various application feature models and identifying feature constituent levels for controlling the consistency among them. A unified feature consists of common attributes and methods for all the supported application features.

Individual work on CAD and FEM models has been done mostly with the help of Knowledge based Engineering. Some of the techniques employed for these individual systems can be brought together along with parametric modeling to improve the effectiveness of CAD–CAE integration. Peak [35] described problems associated with CAD and CAE interoperability, fine grain associativity gaps and software tools' limitations such as knowledge modularity, reusability, and accessibility, directionality, fidelity, control, and multi-disciplinary associativity. Work also focussed on mapping various attributes between CAD and CAE in order to reduce the overall time and cost associated with design process. Zeng et al. [36] suggested the use of *ZAP*, knowledge based FE modeling method, to reduce design time and suggested CAD–FEA integration at knowledge level and stressed the importance of automation in idealization of CAD and mesh generation. Lee [37] focussed on creating a single model containing both CAD and CAE features and explored the advantages of a *common modeling environment* and *bidirectional* CAD and CAE integration with multiple feature representations and limited automation.

3. What is CDM?

Following the conventional design process and standards, after starting the design project, the user is required to input the "*design requirements and specifications*". Then based on the product development knowledge, all the design parameters at the engineering conceptual design level are determined and embedded into the conceptual design models with CAD tools. Engineering analysis with CAE tools is conducted to verify the design concepts at different abstract levels and from different aspects.

It is the proposed concept that a centralized parameter repository that contains those driving design and analysis parameters as well as their explicit constraints is developed as a common data model (CDM) such that the characteristics of conceptual design and the CAE analysis settings are kept in a systematic form and can be managed for their consistency. In other words, the Common Data Model is made of all the design semantic parameters required to build CAD model, FE mesh model and to conduct engineering analysis with the assistance of knowledge based tools and software

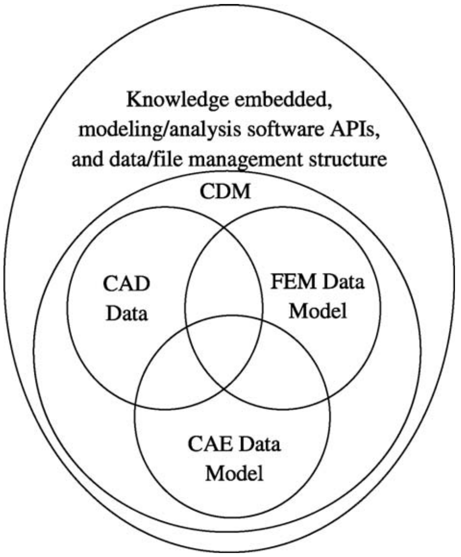
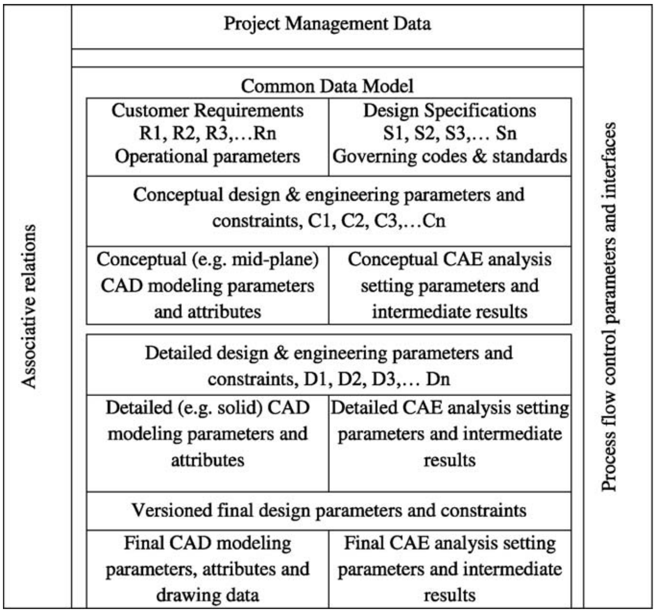


Fig. 1. General working aspects of CDM.


Associative relations

Project Management Data

Common Data Model

Customer Requirements R1, R2, R3,…Rn Operational parameters

Design Specifications S1, S2, S3,… Sn Governing codes & standards

Conceptual design & engineering parameters and constraints, C1, C2, C3,…Cn

Conceptual (e.g. mid-plane) CAD modeling parameters and attributes

Conceptual CAE analysis setting parameters and intermediate results

Detailed design & engineering parameters and constraints, D1, D2, D3,… Dn

Detailed (e.g. solid) CAD modeling parameters and attributes

Detailed CAE analysis setting parameters and intermediate results

Versioned final design parameters and constraints

Final CAD modeling parameters, attributes and drawing data

Final CAE analysis setting parameters and intermediate results

Process flow control parameters and interfaces

Fig. 2. Structure of CDM with the progress of design process [38].

APIs. Fig. 1 shows the basic concept of data management system with CDM.

The proposed design procedure using CDM to integrate CAD and CAE is based on two corner stones, i.e. parametric design and analysis in CAD and CAE environments respectively, and the change management strategy that support a progressive and cyclic approach for the iterations of product conceptual and detailed design evolution. CDM can be captured in a data structure and stored in a neutral data file at the same time. The design data model generated this way can be recorded, documented and rationalized along with the different phases of a product lifecycle.

Hence, this CDM is a dynamically activated data file and its contents are increased and the engineering intent embedded is detailed gradually in stages over the period of design consolidation. Based on the CDM, a design program further calculates and/or selects all the required geometric and analysis parameters according to the standard industrial design procedures and the required regulatory codes. The content in CDM is of three general categories (1) geometric parameters; (2) Non-geometric functional parameters; (3) intermediate design related parameters.

CDM assists in retaining all the information at a centrally organized data structure and acts as a system “switch board” for all the parametric input of CAD, FE and CAE user-defined interfaces to automatically create all the required computer models. Information in CDM about parameters not only contains the numeric values but also the specific units associated. All the information is carefully represented in some specific data structures that can be directly transmitted to and from the used program API functions and arranged into the readable with concise comments or instructions. Note that the arrangement of information in the CDM and its data file can be customized depending upon the software tool requirement. For example, the Siemens NX 6 parametric expression input file requires information in the form of *“[UNIT] NAME = VALUE”*. For other data exporting and importing purpose, depending upon the software input requirement, the intermediate file format of the CDM can be manipulated with data and file handling algorithms, such as using “.XML” format. In current study, the data file is first generated as a text file (.txt) and then converted into an “expression” (.exp) file which is used as parametric input for the NX software tool.

To make use of the design change control mechanisms with CDM in a parametric approach, the CDM needs to be associated and supported with the functional programs either automatically or interactively to keep its structure and contents consistent and updated. Thus the CDM management system is always associated with its data file as a permanent repository, and a set of fully functioning, parametric, knowledge driven design and analysis programs in the background.

The comprehensive description of the design models needs a large amount of data provided by the users throughout development process with tedious and repetitive input operations. Thus expert system coupled with artificial intelligence technology can serve the purpose. In order to represent entire design data in terms of parameters, the CDM has to represent

(1) Meaningful design history by versions of CDM records each of which includes embedded design intentions collectively as a “state” of the design evolution.
(2) Those referenced common parameters that constituent the required constraint and interference relations among different modeling operations.
(3) The complete data set to ensure the robustness of reconstruction.
(4) Independent and neutral manipulation capability interfaced with CAD and FE software system.
(5) Data system which can be easily understood for engineers and associated with respective aspects and features in the model.

Structure of the CDM shown in Fig. 2 follows the proposed design procedure. Initial entry to CDM contains design and operational requirements provided by the designer. These inputs are then used to first calculate non-geometric intermediate design information like additional operating parameters as introduced in the section of “Design calculations” previously. The first set of complete parameters to build CAD model and CAE analysis are generated for the conceptual design. These parameters include geometric dimensions, design parameters and limits and constraints required to generate mid-plane CAD model, FE mesh and CAE analysis. The conceptual design procedure is repeated until the desired configuration is obtained. In the next phase, all the parameters required for the detailed design such as the dimensions for the internal components and constraints are generated automatically using the program code. These parameters along with previously refined parameters from conceptual model provide required parameters

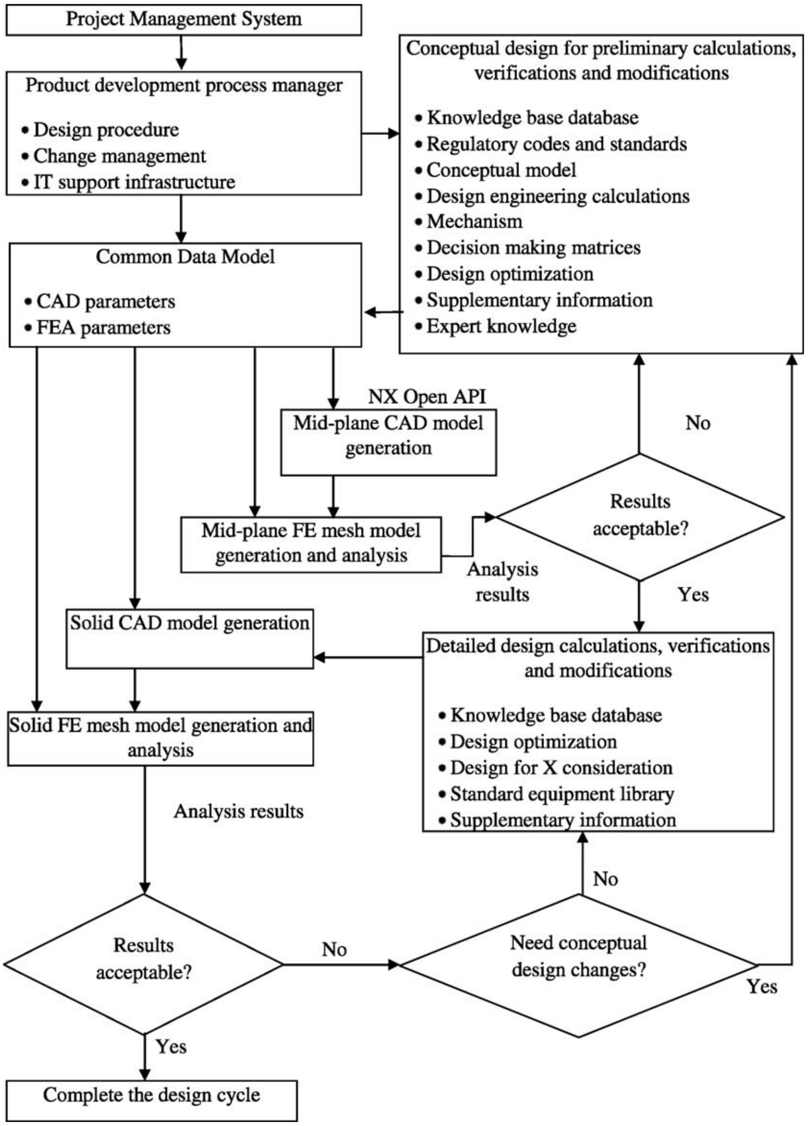


Fig. 3. Proposed design process with CAD/CAE integration [38].

for the final solid model. This final list of parameters is then used to generate 3D solid CAD and FE model and the final CAE analysis. These final parameters are then refined with each design iteration till designer's intents are met. The final parameters are the versioned refined parameters which can be used to create a final model further used for manufacturing. With a similar software setup at each workstation, a commonly placed data file can be used in collaborative environment by a development group. Coupled with optimization algorithms and detailed manufacturing embedded knowledge, CDM can be further refined to include manufacturing details such as tolerances.

4. Proposed design process with CDM

CDM acts as a kernel data structure connecting all application programs, supported with file and data management software modules that control the user interface as well as the information security and integrity. Ideally, there should be a system for all applications to be combined in a single interface. Also the system should be open, or to be able to enhance by adding new application or taking advantage of improvements in technology without invalidating previously obtained data.

The basic purpose of this study was to develop an efficient and time saving design development procedure. Ideally, a fully integrated design method can be developed to automatically generate all the engineering information, computer models and analysis results. To be realistic, such a method could exist for those products need the reuse of a well-established and generic design procedure with a constant designing methodology like pressure vessels. A knowledge based and parametrically generative approach is taken for both CAD modeling and CAE analysis interfaces.

Just like normal design practice the process, as shown in Fig. 3, is divided into a number of stages which follow similar logic in the program code. The design processes are arranged in such a manner that they flexibly follow the conventional as well as advanced, integrated, and parametric product design methodology. In the proposed method, CAD and CAE integration happens at parameter levels of CDM.

During the initial stage, the customer's requirements and technical requirements are accepted by the designer become the initial input data of CDM. These inputs are designed and used in the engineering knowledge embedded calculations of a product model generation program. The equations specifically used for a two phase oil and gas separator design, are to be introduced in Section 5. In this stage, the CDM serves to record the driving design parameters and key constraints. Note the product model should be generated with the help of conceptual engineering knowledge, industrial standards and codes through object-oriented programming coherently.

To explain the product development process with more insight, an example of pressure vessel, i.e. a two phase oil–gas vertical separator is used throughout the paper as the case studied.

As commonly started, to make a preliminary quick evaluation of the developed design concept, an abstract CAD model is created automatically by using the necessary APIs. As shown in Fig. 3, for a vertical separator, during this stage, a planar (mid-plane) CAD model using parameters from CDM is automatically generated. Next, the CAD model generated is used as the geometric input to create a finite element mesh model. FE model utilizes meshing and material parameters from CDM automatically to assign mesh physical and material properties to the model.

Since the model has a planar CAD model as base, the elements generated are also planar (2D). In case of design of a thin vessel like separator, the mid-plane for the design is assumed to be at the geometric midpoint of the thickness for ease of calculations. The mesh model thus created is then used for computational analysis of the model in a CAE environment.

During analysis design specifications such as load values can be directly inserted from CDM via programming. Also all the constraints associated with the analysis can also be stored in the form of embedded knowledge specific to a particular design object and applied to the analysis model. Results obtained from the analysis are then provided to the user to make a decision for the validation of the design and to trigger any changes if required.

If the design needs further changes to fit the requirements, the designer is given multiple options based on general change scenarios and then new changes are incorporated into the CDM. Then changes are implemented by re-running the model generation program to update all the related parameters of the design. This new set of parameters is then used again automatically to create the model for analysis through the mesh generation and CAE setting programs. After that, a new set of results are provided to the designer for verification. This conceptual mid-plane design cycle continues till desired results are obtained.

Once the conceptual design stage is completed, detailed design phase kicks in. Usually, to enable more detailed analysis and finalize the design model, a much more detailed solid (3D) CAD model is generated using the detail design parameters predefined in the CDM. Similarly, CAE model has to be detailed to fully reflect the features of the new geometry defined. So, a solid (3D) FE model (solid mesh model) is created based on the solid CAD model. This FE model is then used for final numerical analysis in CAE software. Like the mid-plane phase before, the constraints and their locations are built into the user-customized CAE analysis program in the form of embedded knowledge. The change management is similar to the conceptual design stage.

Detail design iterations occur through the designer's evaluation and automatic propagation of changes to all the parameters in CDM and subsequently to all the computer models. Updated changes can be automatically reflected in both CAD and CAE models by executing the associated generation programs again iteratively. This iteration continues until satisfactory results are obtained. Depending on the intention of design changes, the process can be rolled back to either conceptual design modeling or detailed design modeling stage.

The final detailed design parameters are extracted from the CAD model; and they are recorded in the CDM and provided to the designers as well as other users via different required output formats. During each stage, the CDM information associated with every cycle is stored separately to maintain a history of design revision cycles. Since computer models can be automatically generated for any stage cycle with the help of CDM, models of a particular stage can be reproduced automatically through API programming. Hence, potentially, many configurations of a product family can be derived for comparison or mass customization purposes. Further, such a system enables user to input desired standard sizes for various components which then the program code uses during the automated design process.

In a design process, the change in scope calls for a considerable increase in the engineering efforts due to the dependences of associated features, while the changes in the sequence of feature creation impose even more complicated "patching" work. Most of the efforts associated with design changes are towards re-engineering and remodeling in order to adapt with user requirements. Each change made in the geometry of the design equally has to be propagated to CDM and all the other aspect of the design. In order to successfully propagate the changes throughout the process, the modeling and analysis software, i.e. a knowledge based generation module in the prototype package, should be developed with logics and functions capable of supporting the changes. More research work is to be expected to work out a generic solution.

Depending upon the availability, proposed method can accommodate any programming software tool and CAD and CAE software tools with API capabilities. Fig. 4 gives the pseudo-code structure of the overall proposed design process. Fig. 5 shows the CAD generation process while Figs. 6 and 7 show the pseudo-code structures of finite element meshing and CAE analysis processes respectively.

5. Construction of the CDM for an example two phase oil–gas separator

The example separator is designed with the reference to [39] and according to American Society of Mechanical Engineers' Boiler and Pressure vessel Code (ASME Code) section VIII. Pressure vessels are designed to withstand the loadings exerted by internal and external pressure, weight of the vessel, reaction of support, and impact. Temperature, pressure, feed composition and its mass flow rate is considered to select type and design of vessel and to come up with the dimensions of vessel.

5.1. Engineering calculations

As usual, engineering calculations have to be dealt with systematically. In this work, they are embedded by programming them into a procedure when initiating the CDM based on the customer's requirement and the designer's specifications. They are taking as constraints. Although there is certainly a room to make them in a more organized and modular system structure, due to the limitation of time available for this particular work, they were simply implemented in a C++ code program.

For this particular study the only load considered are internal pressure and temperature. Vessel size is decided depending upon the flow rate requirement. Table 1 gives the data structure suggested for the CDM for the design of a two phase oil-gas separator.

5.1.1. Separator flow details

(1) First calculate the density of liquid (oil), which can be calculated by the following formula

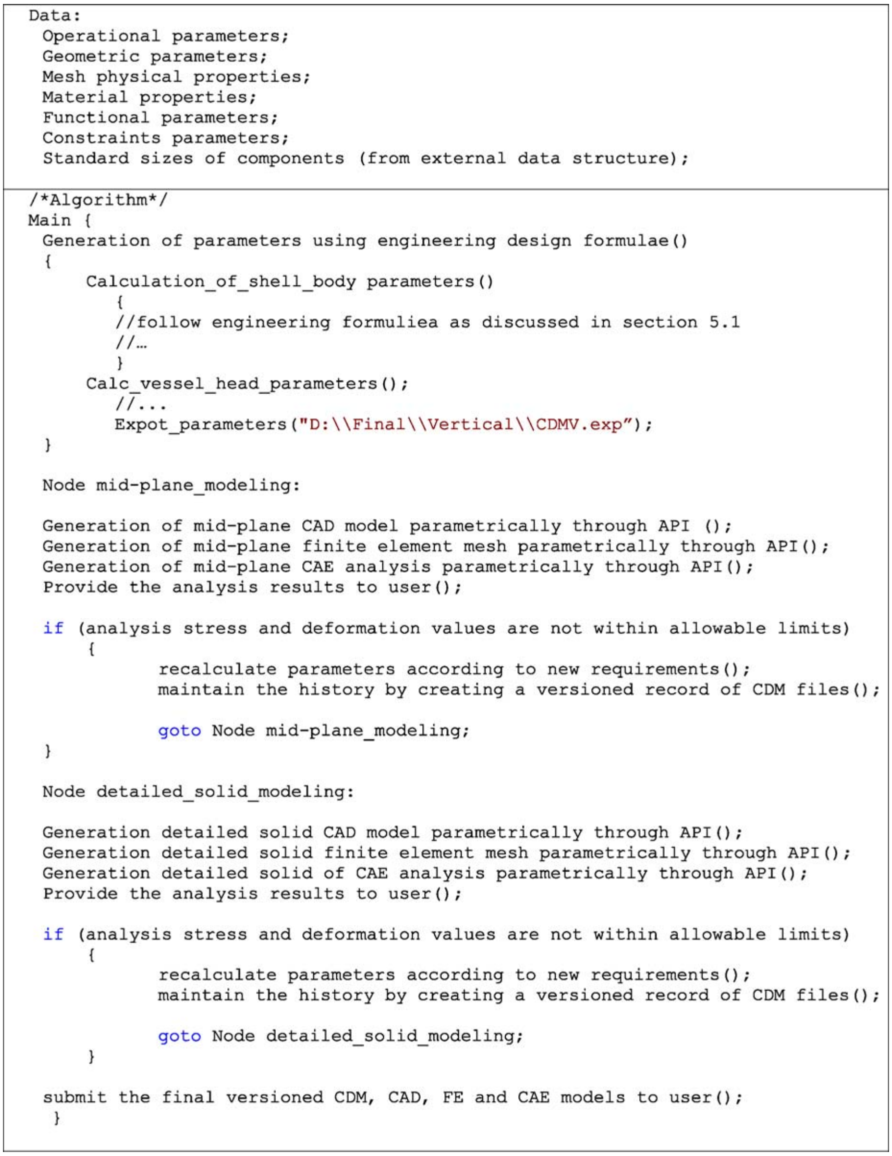
$$\rho l = \frac{141.5}{131.5 + \mathrm{API}^{\circ}}. \qquad (1)$$

(2) Molecular weight (MW) of the gas can be found as the specific gravity (SGg) of gas is given by the following equation

$$\mathrm{MW} = 29 \times SGg. \qquad (2)$$

(3) The compressibility factor is assumed as

$$Z = 0.84.$$



```
Data:
 Operational parameters;
 Geometric parameters;
 Mesh physical properties;
 Material properties;
 Functional parameters;
 Constraints parameters;
 Standard sizes of components (from external data structure);
```

```
/*Algorithm*/
Main {
 Generation of parameters using engineering design formulae()
 {
     Calculation_of_shell_body parameters()
        {
        //follow engineering formuliea as discussed in section 5.1
        //…
        }
     Calc_vessel_head_parameters();
        //...
        Expot_parameters("D:\\Final\\Vertical\\CDMV.exp");
 }

 Node mid-plane_modeling:

 Generation of mid-plane CAD model parametrically through API ();
 Generation of mid-plane finite element mesh parametrically through API();
 Generation of mid-plane CAE analysis parametrically through API();
 Provide the analysis results to user();

 if (analysis stress and deformation values are not within allowable limits)
     {
          recalculate parameters according to new requirements();
          maintain the history by creating a versioned record of CDM files();

          goto Node mid-plane_modeling;
 }

 Node detailed_solid_modeling:

 Generation detailed solid CAD model parametrically through API();
 Generation detailed solid finite element mesh parametrically through API();
 Generation detailed solid of CAE analysis parametrically through API();
 Provide the analysis results to user();

 if (analysis stress and deformation values are not within allowable limits)
     {
          recalculate parameters according to new requirements();
          maintain the history by creating a versioned record of CDM files();

          goto Node detailed_solid_modeling;
     }

 submit the final versioned CDM, CAD, FE and CAE models to user();
  }
```

Fig. 4. Pseudo-code structure for overall design process.

(4) Compressibility factor (Z) value is required to calculate the density of gas (ρg) by the following formula

$$\rho g = \frac{2.7 \times SGg \times P}{T \times Z}. \tag{3}$$

(5) The drop diameter size (dm) is taken as input from user.

(6) Drag coefficient (CD), which has been found to be a function of the shape of the particle and Reynolds Number of the flowing gas. For the purpose particle shape is considered to be solid, rigid sphere

$$CD = \left[\left(\frac{24}{RE}\right) + \left(\frac{3}{RE}\right)^{0.5} + 0.34\right] \tag{4}$$

where, Reynolds Number (RE) is given by the following formula

$$RE = 0.0049\left(\frac{\rho g \times dm \times \nu t}{\mu}\right). \tag{5}$$

In this form, a trial-and-error solution is required since both particle size dm and terminal velocity νt are involved. Where, terminal velocity is given by the following equation:

$$\nu t = 0.0119\left[\left(\frac{\rho l - \rho g}{\rho g}\right)\frac{dm}{CD}\right]^{0.5}. \tag{6}$$

To get constant value for drag coefficient, value is assumed to find terminal velocity and Reynolds Number and which will be used in getting drag coefficient. This cycle will take place until all parameters become constant.

5.1.2. *Design for separator shell dimensions*

(1) The shell diameter is calculated as follows for gas capacity considering the required height of liquid, any diameter greater than the minimum required for gas capacity can be chosen

$$D = \sqrt{5040\left(\frac{T \times Z \times Qg}{P}\right)\left[\left(\frac{\rho g}{\rho l - \rho g}\right)\frac{CD}{dm}\right]^{0.5}}. \tag{7}$$

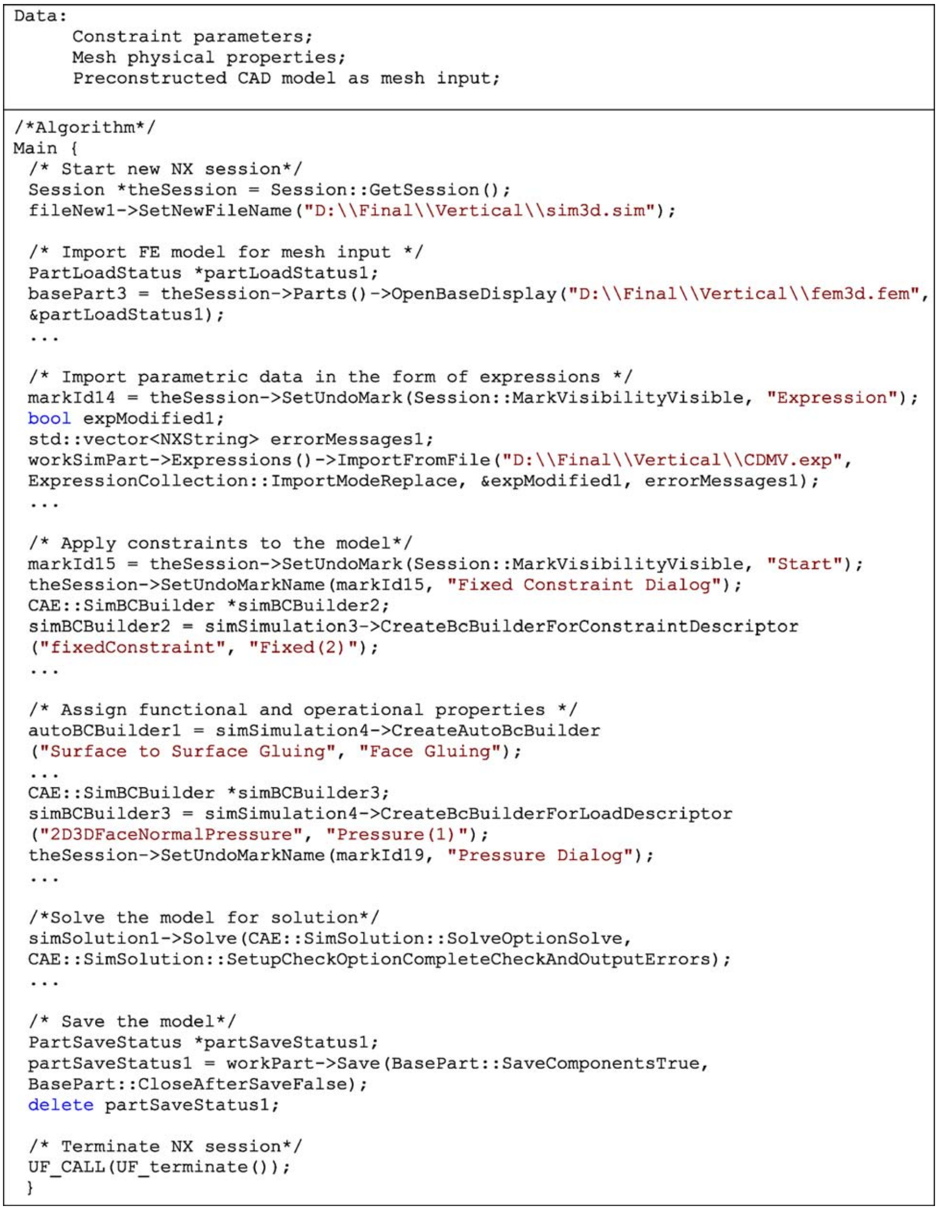
(2) For liquid capacity to remain in the vessel the term used is called retention time tr in minutes. The liquid retention time requirement specifies a combination of diameter and liquid height and

```
Data:
 Geometric parameters;
 Constraints parameters;
 Standard sizes of components (from external data base);

/*Algorithm*/
Main {
 /* Start new NX session*/
 Session *theSession = Session::GetSession();
 FileNew1->SetNewFileName("D:\\Final\\Vertical\\cad3d.prt");
 ...

 /* Import parametric data in the form of expressions */
 markId4 = theSession->SetUndoMark(Session::MarkVisibilityVisible, "Expression");
 bool expModified1;
 std::vector<NXString> errorMessages1; workPart->Expressions()-> ImportFromFile
 ("D:\\Final\\Vertical\\CDMV.exp",ExpressionCollection::ImportModeReplace;
 ...

 /* Create vessel body structure */
 cylinderBuilder1->Diameter()->SetRightHandSide
 ("Shell_diameter+(2*Shell_thickness)");
 cylinderBuilder1->Height()->SetRightHandSide("Shell_length");
 theSession->SetUndoMarkName(markId5, "Cylinder Dialog");
 ...

 /*Create head structure, nozzle structures and internal details*/
 ...

 /* Save the model*/
 PartSaveStatus *partSaveStatus1;
 partSaveStatus1 = workPart->Save(BasePart::SaveComponentsTrue,
 BasePart::CloseAfterSaveFalse);
 delete partSaveStatus1;

 /* Terminate NX session*/
 UF_CALL(UF_terminate());

 }
```

Fig. 5. Pseudo-code structure for CAD model generation.

```
Data:
 Material parameters;
 Functional details;
 Preconstructed CAD model as geometric input;

/*Algorithm*/
Main {
 /* Start new NX session*/
 Session *theSession = Session::GetSession();
 fileNew1->SetNewFileName("D:\\Final\\Vertical\\fem3d.fem");

 /* Import CAD model for geometry input */
 PartLoadStatus *partLoadStatus1;
 basePart3 = theSession->Parts()->OpenBaseDisplay("D:\\Final\\Vertical\\cad3d.prt",
 &partLoadStatus1);
 ...

 /* Import parametric data in the form of expressions */
 markId14 = theSession->SetUndoMark(Session::MarkVisibilityVisible, "Expression");
 bool expModified1;
 std::vector<NXString> errorMessages1;
 workFemPart->Expressions()->ImportFromFile("D:\\Final\\Vertical\\CDMV.exp",
 ExpressionCollection::ImportModeReplace, &expModified1, errorMessages1);
 ...

 /* Create a finite element mesh*/
 mesh3dTetBuilder1 = meshManager1->CreateMesh3dTetBuilder(nullCAE_Mesh3d);
 theSession->SetUndoMarkName(markId6, "3D Tetrahedral Mesh Dialog");
 ...

 /* Assign mesh physical properties */
 CAE::PropertyTable *propertyTable1;
 propertyTable1 = mesh3dTetBuilder1->PropertyTable();
 propertyTable2->SetScalarPropertyValue("quad mesh overall edge size", expression1);
 ...

 /* Save the model*/
 PartSaveStatus *partSaveStatus1;
 partSaveStatus1 = workPart->Save(BasePart::SaveComponentsTrue,
 BasePart::CloseAfterSaveFalse);
 delete partSaveStatus1;

 /* Terminate NX session*/
 UF_CALL(UF_terminate());

 }
```

Fig. 6. Pseudo-code structure for FE mesh model generation.



```
Data:
     Constraint parameters;
     Mesh physical properties;
     Preconstructed CAD model as mesh input;
```

```
/*Algorithm*/
Main {
 /* Start new NX session*/
 Session *theSession = Session::GetSession();
 fileNew1->SetNewFileName("D:\\Final\\Vertical\\sim3d.sim");

 /* Import FE model for mesh input */
 PartLoadStatus *partLoadStatus1;
 basePart3 = theSession->Parts()->OpenBaseDisplay("D:\\Final\\Vertical\\fem3d.fem",
 &partLoadStatus1);
 ...

 /* Import parametric data in the form of expressions */
 markId14 = theSession->SetUndoMark(Session::MarkVisibilityVisible, "Expression");
 bool expModified1;
 std::vector<NXString> errorMessages1;
 workSimPart->Expressions()->ImportFromFile("D:\\Final\\Vertical\\CDMV.exp",
 ExpressionCollection::ImportModeReplace, &expModified1, errorMessages1);
 ...

 /* Apply constraints to the model*/
 markId15 = theSession->SetUndoMark(Session::MarkVisibilityVisible, "Start");
 theSession->SetUndoMarkName(markId15, "Fixed Constraint Dialog");
 CAE::SimBCBuilder *simBCBuilder2;
 simBCBuilder2 = simSimulation3->CreateBcBuilderForConstraintDescriptor
 ("fixedConstraint", "Fixed(2)");
 ...

 /* Assign functional and operational properties */
 autoBCBuilder1 = simSimulation4->CreateAutoBcBuilder
 ("Surface to Surface Gluing", "Face Gluing");
 ...
 CAE::SimBCBuilder *simBCBuilder3;
 simBCBuilder3 = simSimulation4->CreateBcBuilderForLoadDescriptor
 ("2D3DFaceNormalPressure", "Pressure(1)");
 theSession->SetUndoMarkName(markId19, "Pressure Dialog");
 ...

 /*Solve the model for solution*/
 simSolution1->Solve(CAE::SimSolution::SolveOptionSolve,
 CAE::SimSolution::SetupCheckOptionCompleteCheckAndOutputErrors);
 ...

 /* Save the model*/
 PartSaveStatus *partSaveStatus1;
 partSaveStatus1 = workPart->Save(BasePart::SaveComponentsTrue,
 BasePart::CloseAfterSaveFalse);
 delete partSaveStatus1;

 /* Terminate NX session*/
 UF_CALL(UF_terminate());
 }
```

Fig. 7. Pseudo-code structure for CAE analysis.

is taken as input from user. The height of the liquid (h) in inches is calculated by the following formula

$$h = \frac{tr \times Ql}{0.12 \times D^2}. \tag{8}$$

(3) Calculate seam to seam length (Lss) in ft. The seam to seam length Lss of the vessel should be determined from the geometry of the vessel once a diameter is known

$$Lss = h + 76. \tag{9}$$

(4) Once shell diameter and seam to seam length is calculated, next standard sizes are selected to compute slenderness ratio (Lss/D), which is usually in the range of 3–4. If the ratio value is greater than 4, then next standard values are assumed until the required ratio is obtained.

(5) Head depth Hh in inches for spherical head (considered for this study) is given by the following equation.

$$Hh = \frac{D}{2}. \tag{10}$$

5.1.3. Design of separator details

(1) Required material properties obtained for user are Yield strength (Sy) and Poisson's ratio. The vessels are designed in accordance with Division 1 rules thus the factor of safety considered is 4. Thus allowable stress value for shell is

$$Ss = Sh = Sn = \frac{Sy}{4}. \tag{11}$$

(2) The required joint efficiency (E) is obtained from the user.

(3) The required corrosion allowance (CA) is also taken as a user input.

(4) Shell thickness ts (in) can be found as per ASME division VIII and given by.

$$ts = \frac{P \times D}{2[(Ss \times E) - (0.6 \times P)]} + CA. \tag{12}$$

(5) Head thickness th in inches as per ASME code for vessel is calculated by the following formula. Where Sh is a maximum

Table 1
Typical parameter data structure of CDM.

CDM parameter name	Engineering parameter symbol	Definition	Unit
Customer requirements			
R1	*dm*	Droplet size in fluid to be separated	μm
R2	*Ql*	Liquid flow capacity	BPD
R3	*Qg*	Gas flow capacity	MMscfd
R4	*tr*	Retention time	min
R5	μ	Viscosity of the fluid	cp
Design specifications (Including input constraints for finite element analysis)			
S1	*P*	Operating pressure	psi
S2	*T*	Operating temperature	°F
S3	API°	Specific gravity of oil	–
S4	*SGg*	Specific gravity of gas	–
S5	*Ss*	Material Strength	psi
S6	*E*	Joint efficiency	–
S7	*W*	Vessel weight	lb
Parameters needed to build conceptual design model			
C1	*D*	Shell diameter	in.
C2	*Lss*	Shell length	in.
C3	*Hh*	Head height	in.
C4	*dnx*	Nozzle diameters	in.
C5	*dnlx*	Nozzle location dimensions	in.
C6	*sx*	Support dimensions	in.
Additional parameters associated with construction of detailed design model			
D1	*tx*	Component thickness	in.
D2	*idx*	Inlet diverter parameters	in.
D3	*vbx*	Vortex breaker parameters	in.
D4	*MEx*	Mist extractor parameters	in.

allowable stress in psi for the material used in head which in this study considered same as the shell material (S).

$$th = \frac{P \times D}{(2 \times Sh \times E) - (0.2 \times P)} + CA. \tag{13}$$

(6) Shell thickness and head thickness is then selected as the next higher value from the standard commercially available plate sizes in inch given below.

(7) The inlet and outlet nozzles are selected according to the flow rate required as below

$$dn = \sqrt{\frac{4 \times Q}{\pi \times vin}}. \tag{14}$$

The flow rate is calculated as

$$Qf = Ql + (166.67 \times Qg). \tag{15}$$

(8) Nozzle thickness is also selected in accordance with ASME vessel design code as below. The nozzle is assumed to be made of same material as the shell

$$tn = \frac{P \times dn}{2[(Sn \times E) - (0.6 \times P)]} + CA. \tag{16}$$

(9) Once thickness obtained, the required nozzle is selected from the standard commercially available pipe sizes below with required standard thickness mentioned above.

5.1.4. Separator internal components

(1) Inlet diverter dimensions (*idx*) depend upon the dimensions of the inlet nozzle diameter. These parameters are direct numerically related and are further usually selected on the basis of expert practice and available inventory [39].

(2) Vortex breaker dimensions (*vbx*) are calculated using the outlet nozzle diameter. The load associated with vortex breaker is very small compared to other components and thus is of a standard thickness and usually manufactured for the least material requirement and ease of installation.

(3) Mist extractor (*MEx*) are usually of standard sizes and the mist extractor support dimension are calculated using shell dimensions Mist extractor mesh element thickness depends upon the standard available elements and various element types.

5.2. Generation of CDM based on the analytical design process

The three basic information sets used in the program to generate the data model are geometric information, engineering rules, regulatory standards.

CDM has to be made in such a way that it should be simple, without any unnecessary details but it should still possess all the required information organized by sub-domains of the design scope and stages. Since the entire design process reliability depends upon CDM, information in CDM should be accurate and every parameter must be exhaustively mapped with those corresponding related feature. As explained in the design process, CDM information is used to construct 3D solid as well as mid-plane representations of same design object. Since CDM aides in automatic CAD and CAE integration at parametric level, the content of the CDM and the data file itself is generated and managed automatically via a customized and integrated design and analysis system.

Fig. 8 shows the partial data structure of CDM for the design of vertical separator design. There are various parameters associated with design with some parameters getting used in multiple applications as highlighted. Most of the parameters are refined during conceptual phase and are used in detailed design phase along with additional details for full representation.

6. Parameter semantic map of CDM

As explained earlier, CDM is a collection of parameters which, in turn, forms all the features in the design. One of the key properties of a design is that all the parameters are more or less interdependent and are semantically connected to each other in the engineering calculation program. To maintain the associativity between all the parameters involved in the design throughout the design process, the relationship between them needs to be identified. As shown in Fig. 9, dependences between various parameters affect the development of the design as well as propagation of the change. Change in any one of the design parameters has an impact on rest of the design. Moreover, the relationship between various parameters is maintained through embedded knowledge in the computer program.

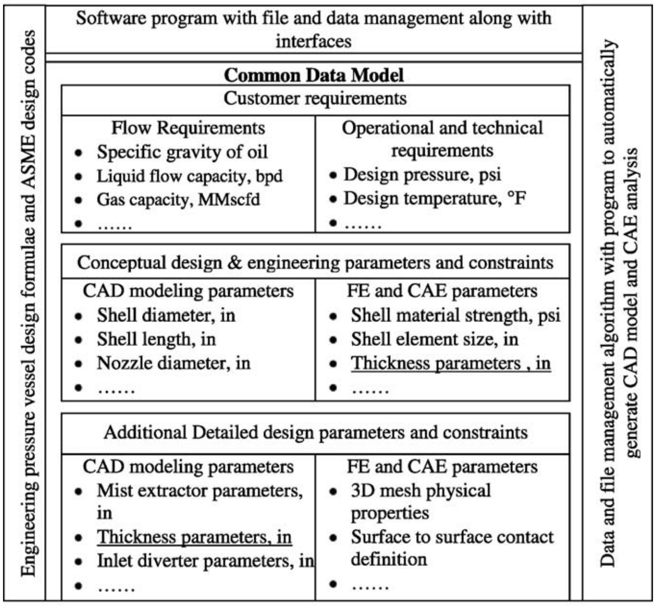
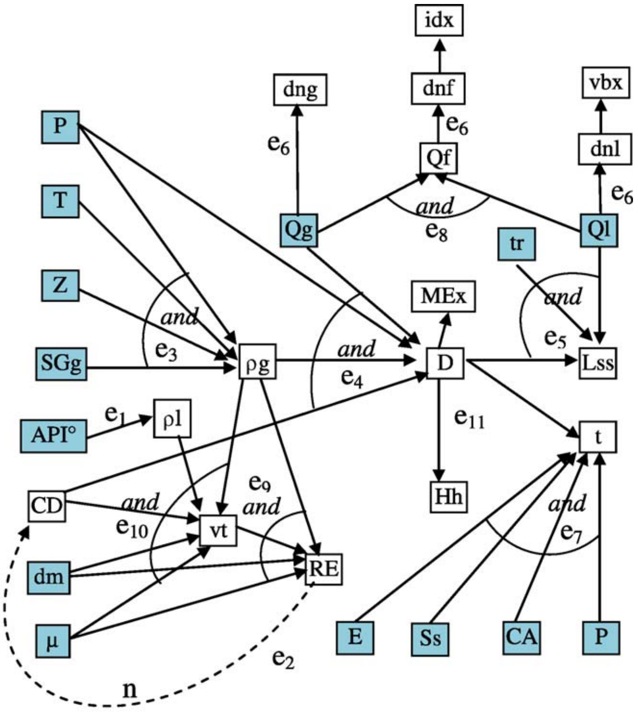


Fig. 8. Partial CDM data for vertical separator design.



List of constraining equations:

e_1 : Eq. (1)
e_2 : Eq. (4)
e_3 : Eq. (3)
e_4 : Eq. (7)
e_5 : Eq. (8) and (9)
e_6 : Eq. (14)
e_7 : Eq. (12) and (13)
e_8 : Eq. (15)
e_9 : Eq. (5)
e_{10} : Eq. (6)
e_{11} : Eq. (10)

Notes:

- Symbols in shaded boxes are known parameters
- Refer to the nomenclature for the definitions of the parameters.

Fig. 9. Parameter semantic map for vertical separator vessel.

The semantic links of the parameters in CDM follows certain patterns in accordance to the established design procedures and codes such as those laid down for pressure vessel design under ASME codes. The first set of parameters which are the user input and the known values, govern the calculations for the parameters associated with conceptual mid-plane design. Parameters associated with detailed design depend on all the parameters in the conceptual design as well as input parameters. Various parameters are entered into the CDM in the same order as per they are created automatically along the process.

However, CDM alone is simply a data file of some sort with all the data thus in order to associate information in it and to establish an automatic semantic relationship, a set of program interfaces are essential to mange those constraints or dependences. The nature of semantic relations depends upon the nature of parameters and their application in forming various design features. Progressively, it can be appreciated that the initial sets of parameters in the form of user input are of functional and operational type, for example they also include parameters associated with material properties. With the help of design intelligence such as those related to flow and operational relations in pressure vessels, the initial set of parameters then produces the intermediate set of mixed functional and geometric parameters. Finally through engineering calculations and selection from standard sizes, a final set of geometric and functional parameters is generated which are used for model generation and analysis.

7. Dynamic data flow and change management

In this separator case, after every modeling cycle, the user is given the simulation analysis results. The static simulation results usually produce maximum stress and maximum deformation values with locations. Depending upon the standard used, quality check requirements and design practice, by checking the simulation results, the user can choose to change the design. Program code used to build CDM and design models further gives the user several options to make changes to design. Any change to design has to first take effect at CDM since it governs all the further process. Options for changes include operating conditions and material. Input from user is taken as a trigger to re-run the knowledge embedded program code to recalculate all the values again and are stored in CDM again. Since CDM is a data file in a generally accessible format, the user may choose to make changes directly with the file. As explained earlier, all the parameters in CDM are semantically associated with each other therefore changes made through the program code will always end up modifying all the related parameters.

In order to change a specific parameter like feature thickness without changing any other parameter, it is convenient to directly change the CDM. Before the design enters into a new iteration, the earlier version of the design data which is in CDM is numbered and stored separately in order to maintain the data from all the design iterations. Since all the models use the parametric information from the CDM, any previous version of the design can be reproduced using the software API and the concerned data file. In general, a model can be defined as the abstract representation of a concept, a phenomenon or a physical entity, a data system can be used to describe and analyze the model totally if all the associated constraints are known.

8. Demonstration of the example product design results

To demonstrate use of CDM, a software prototype to design a two phase oil–gas separator is developed. The package is developed using C++ to embed engineering knowledge and also for file

Table 2
Input design conditions for the vertical two phase oil–gas separator example.

CDM parameter name	Engineering parameter symbol	Definition	Unit	Value
R1	*dm*	Droplet size in fluid to be separated	μm	140
R2	*Ql*	Liquid flow capacity	BPD	2000
R3	*Qg*	Gas flow capacity	MMscfd	10
R4	*tr*	Retention time	min	3
S1	*P*	Operating pressure	psi	1000
S2	*T*	Operating temperature	°F	60
S3	API°	Specific gravity of oil	–	40
S4	*SGg*	Specific gravity of gas	–	0.6
S5	*Ss*	Material strength	psi	20,000
S6	*E*	Joint efficiency	–	0.9

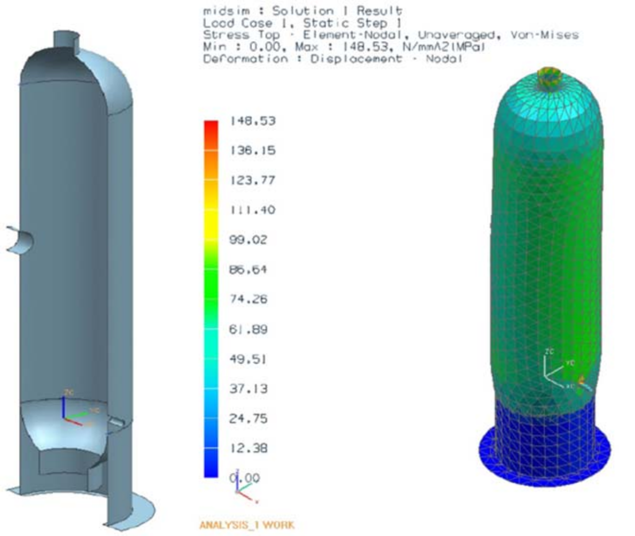
$\boldsymbol{R_n}$: Customer requirement parameters; $\boldsymbol{S_n}$: Specification parameters.

and data management. NX 6 CAD is used for modeling whereas NX Nastran is used for FE modeling and analysis. To automate CAD and CAE process NX Open API is used with C++ as programming base. Design process for the vessels follow the proposed way described in Table 2.

Fig. 10 shows the use of CDM as expressions to construct the CAD model. The expression file is automatically called upon in the program code used to automatically generate the model through the application program interface.

8.1. Conceptual design stage

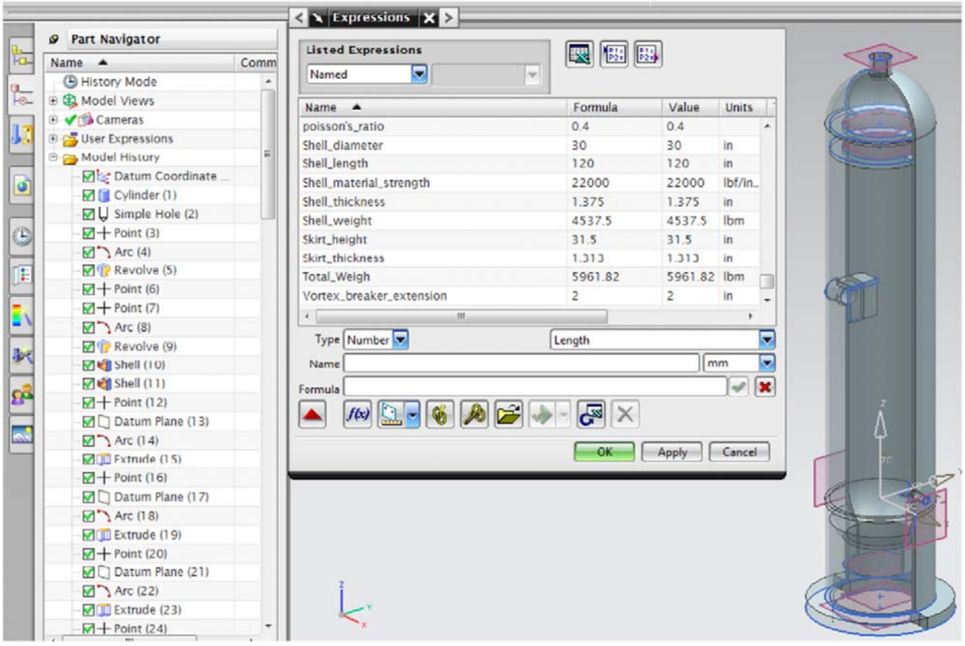
During the first phase of design which is the conceptual phase, the separator model only contains basic parameters. It is essentially a step to verify the design of the basic vessel of the separator. It also contains all the nozzle openings and connections and vessel support. Fig. 11 shows the mid-plane conceptual model for vertical separator. Conceptual model is mid-plane planar model essentially to check the plane stress and plane strain to validate vessel design. The mid-plane CAD model serves as the basis to create the mid place FE model converting the planar model into 2D planar elements. All the vessel components are joined together using 1D bar elements. The 2D elements of the vessel are given thickness equal to the vessel thickness and also each nozzle wall elements are given nozzle



(a) Mid-plane CAD model generated by NX.

(b) Von-Mises stress analysis result generated from NX Nastran (MPa).

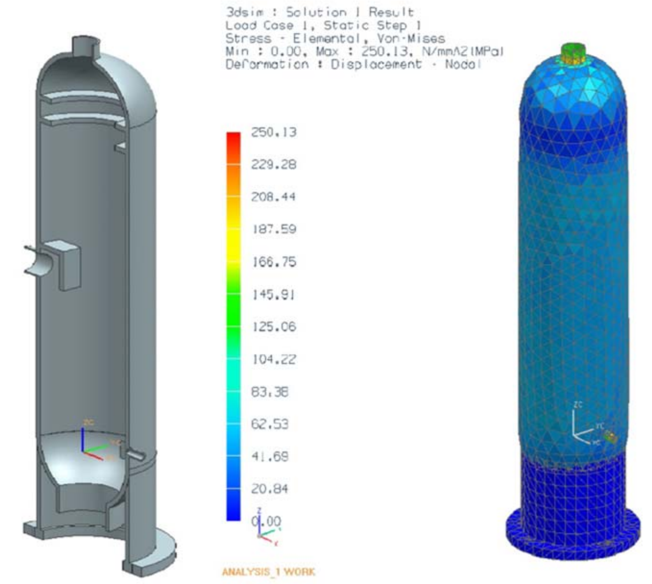
Fig. 11. Parametric conceptual mid-plane model and the final FE analysis result.



Name	Formula	Value	Units
poisson's_ratio	0.4	0.4	
Shell_diameter	30	30	in
Shell_length	120	120	in
Shell_material_strength	22000	22000	lbf/in..
Shell_thickness	1.375	1.375	in
Shell_weight	4537.5	4537.5	lbm
Skirt_height	31.5	31.5	in
Skirt_thickness	1.313	1.313	in
Total_Weigh	5961.82	5961.82	lbm
Vortex_breaker_extension	2	2	in

Type: Number
Length
Name:
mm
Formula:

Fig. 10. Interface between CAD model and CDM through "expression" function.



(a) Solid CAD model generated by NX.

(b) Von-Mises stress analysis result generated from NX Nastran (MPa).

Fig. 12. Parametric 3D model and the final FE analysis result.

thickness. Then the ready FE model is used for simulation. The simulation is run for static load considering internal pressure load and temperature load. For simulation purpose, base of the vessel support is fixed along with the ends of nozzles to simulate contact with ground and pipe continuations respectively. Once the simulation is run the major values to check are maximum deformation and maximum stress. If the results are within acceptable limits, the design is passed on to further stage otherwise the user is prompted through program API to make design changes. Changes made are further verified again by program code to make sure that they follow the standard design procedure and codes. Once verified, the refined parameters in the CDM are again used to conceptual design is finalized, the design process proceeds to the next phase. Even after this phase if during further refinement basic vessel design needs correction, it is possible to get back to this initial iteration as shown in the process diagram in Fig. 3. Considering that all the models in this phase are planar and FE model contains 2D elements, time required to build all the models and the CAE analysis are very less compared to that of detailed 3D model. Also as most of the refinement of major design objects takes place during this phase, it reduces the number of iterations required during the detailed design phase thus reducing the overall time required.

8.2. *Detailed design stages*

During second phase of design process detailed design of separator is produced. Fig. 12 shows detailed 3D models for vertical separator. This model is 3D solid model with full design details. Separator model includes internal details such as internal diverter, vortex breaker and mist extractor support. Just like the mid-plane model, solid 3D models are also generated automatically using NX6 API called NX Open. 3D CAD model is used to create the FE model required to create the simulation model and to perform analysis. This simulation is done with all the internal details, thus is much more detailed as compared to the analysis of the mid-plane analysis. Simulation conditions for solid model analysis are same as mid-plane analysis. All the constraints and loads are also similar. Just like during mid-plane phase the model is refined until desired analysis results are obtained. Parameters checked for design verification include maximum stress and maximum displacement. This is the second iteration in the design process. The versioned solid CAD model is separator structures with all basic essential functional components. The model then applied with required tolerances and process details can be used for manufacturing. The CAD model can then further be used for CAM process. As per the conditional requirements, while manufacturing additional components may need to be added later such as de-foaming plates and flow breakers.

9. Advantages and limitations of the proposed method

The advantages of this approach is that the CAD and CAE integration process with CDM offers centralized design parameters and their data and yet the ease of separate automation for CAD and CAE. It facilitates the manipulation of design data and the control over parameters with the use of engineering knowledge along with CAD and CAE for design cycles. This approach also incorporates use of rules and standards checking in a separate module reducing the dependences among different sub-domain models which have the generic applications as CDM based programming allow flexibility of adopting different practice standards used for design. CDM manipulates data on parametric level thus design changes can be successfully propagated to all the related features of the CAD and CAE models by regeneration which in turn eliminates requirement of specific feature editing and manipulation. The parametric data model developed includes manufacturing consideration on design such as the welding efficiency. CDM data can be further customized with the help of well-organized standard component dimensions and configurations adapted to the proposed process; then the design features can consider the available inventory along with the required installation constraints.

The proposed integration method though quite flexible, still has some limitations, such as the need for the initial CDM parameter and relation identification beforehand to develop the model generation program of the process management module along with the required standards and governing codes. Thus the initial development phase requires considerable programming. Also the design procedure needs to be sorted beforehand along with the required assumptions to build CAD model and CAE analysis and associated constraints to develop the logics required for automatic generation. Thus the process only offers long term efficiency for well-established, generic and set design problems. However, for those cases without established design procedures and with a lot of "ad hoc" user interventions and "rolling" backward or forward, this method seems lack of the flexibility in comparison to interactive modeling and analysis approach.

10. Conclusion

Parametric integration of CAD and CAE using a common data model enables to solve the problem of association of feature based semantic knowledge and the iterations of CAD and CAE interaction cycles. With the help of CDM, it is feasible to integrate design and analysis processes via the associative relations and the built-in interfaces with the CAD and CAE models. With this generative approach of design, design cycles can be coherently modeled with a systematic updating mechanism with reusability of engineering knowledge and the design expertise. With a well managed program design structure, the method is not limited by the software tools used. With a neutral data structure, the common data model (CDM) gives the flexibility of using various CAD and CAE software tools; their APIs and can be used to automate the entire modeling process. Thus, this approach potentially saves a significant amount of time associated with the design process.

CDM via programmed design management structure connects the design models and expert knowledge with any KBE implementation; it separates the programming of design expertise from CAD or CAE modeling hence ensures the reusability of those design procedures once they are created in a computerized design format. All the design and analysis information is stored independent of actual CAD or CAE software tool thus any loss of information during the model translation or derivation can be retrieved from the CDM. CDM also acts as automatic input through API of modeling software tool with the help of parametric modeling capability, thus eliminates need for direct human interaction in the process. This minimizes possibilities of error as well as ensures that the same process flow is followed through different iterations. The complexity, accuracy and quality of design depends upon the embedded knowledge and expertise as well as creating an API template for CAD and CAE, a well developed system with a CDM can efficiently handle complex design problems.

Current work with CDM is limited with only CAD and CAE but the use can be further explored in the fields of CAM and also for other uses such as cost estimation. Future enhancement in the work involves creating a knowledge based software tool for automatic assembly coupled with part template library to deal with more diverse design problems. This study only involves the preliminary design of a pressure vessel type limited to sizing and the essential operational concepts; further work will involve refining the model with more design features to prepare a complete drawing ready for manufacturing.

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